A Review: Numerical Modeling of the Debris Throw of Reinforced Concrete Structures under Internal Explosions

H.S. Lim [1] and K.W. Kang [1]
S.C. Fan [2], Q.J.Yu [2], Y.W. Yang [2],

[1] Defence Science and Technology Agency, 1 Depot Road #03-01J, Singapore 109679 ,
Lhengsoo@dsta.gov.sg

[2] Protective Technology Research Centre, School of Civil and Environmental Engineering,
Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798.

Presenter : Heng Soon, Lim is a Principal Engineer in DSTA, Singapore. He has been working in the field of explosive safety for the last 10 years and is regular participant in the Klotz Group. Heng Soon holds a Bachelor degree from National University of Singapore and a Masters degree in Civil Engineering from Delft University of Technology.

Abstract

DSTA and NTU have been working together to develop a methodology to simulate the breakup and debris throw of reinforced concrete (RC) structures under internal explosion. The numerical simulation simulates the following five phases of the explosion event: internal loading; response and breakup; debris launch; debris trajectory and post ground impact. Results from the simulations of the various stages have been presented and discussed in previous DDESB seminars and other related conferences. This paper serves as an overview of the work done. In addition, the contribution of various parameters to the prediction of such dynamic response is assessed and tabulated.

1. Introduction

For any explosives or ammunition storehouse, there are potential hazards to its surrounding environment. The potential hazards manifest in the form of airblast, fireball/thermal radiation, groundshock and throw of debris and fragments in the event of accidental explosion. To minimize the risk to these hazards, safety distances between the ammunition storehouses and other facilities are prescribed. These safety distances are primarily based on the airblast pressure prediction and the hazard from debris is not adequately addressed.

In order to address the hazard of debris, Defence Science and Technology Agency (DSTA) together with Nanyang Technological University (NTU) of Singapore has been working together in a project to study the breakup of reinforced concrete box structures and subsequently the throw of concrete debris for the last 6 years. The aim of the project is to provide a more accurate numerical model for debris hazard throw which in turn could lead to redefining of the debris Inhabited Building Distance. Results from the various stages of this project have been reported in the past DDESB seminars. The aim of this paper is to summarise the key lessons learnt through these 6 years and identified some of the future works beyond.

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2. Approach to the Debris Prediction Model

It is recognised from the onset of the project that even developing a moderately accurate debris numerical model is an extremely daunting task. To simplify the problem, the debris throw phenomenon has been broadly categorised into 5 main phases: 1) internal blast loading, 2) response and breakup, 3) debris launch, 4) debris trajectory and 5) post ground impact. It must be recognised that these 5 phases are not cleanly demarcated in time and they are not independent of each other.

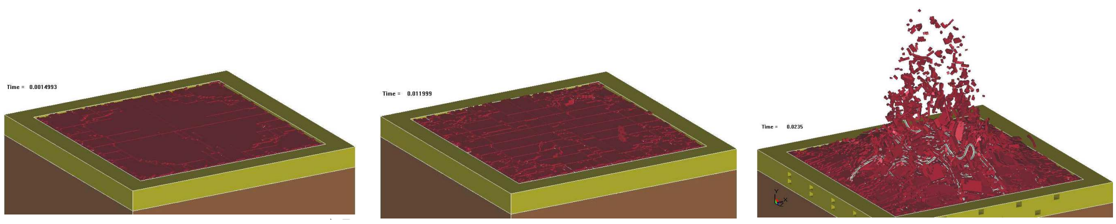
3. Internal Blast Loading

The first step of the debris prediction model is to get a good estimate of the internal blast loading of the structures. For a confined explosion, the internal blast loading on the wall consist a multiple high pressure shock reflections and a much lower pressure quasi-static gas pressure buildup. As energy is imparted to the structure through the shock and gas pressure, the structure deforms, develops cracks and eventually breakup to form debris. When the cracks in the structure develop, the blast pressure will be vented through these cracks.

3.1 Influence of Shock and Gas Loadings

One of the first parameters to be examined is the influence of shock pressure and gas pressure on reinforced concrete structures [1]. For this study, a coupled numerical model for RC slabs under explosive detonation was established, in which the concrete and the reinforcing bars are modelled using independent solid elements with the failure at the concrete-steel interface being determined by the concrete strength.

When the loading density is low (in the order of 0.25kg/m^3), the shock impulse exhibited little influence on the overall slab response as it not high enough to fail the concrete mass extensively. This allows the subsequent slower gas loading to determine the overall deformation and crack patterns on the slab as observed in Figure 1(a) and (b). On the contrary, upon the use of higher loading density (above 2 kg/m^3) in Figure 1(c), the concrete mass is breached much earlier, which will render the subsequent gas loading phase less important in deforming the RC slab.

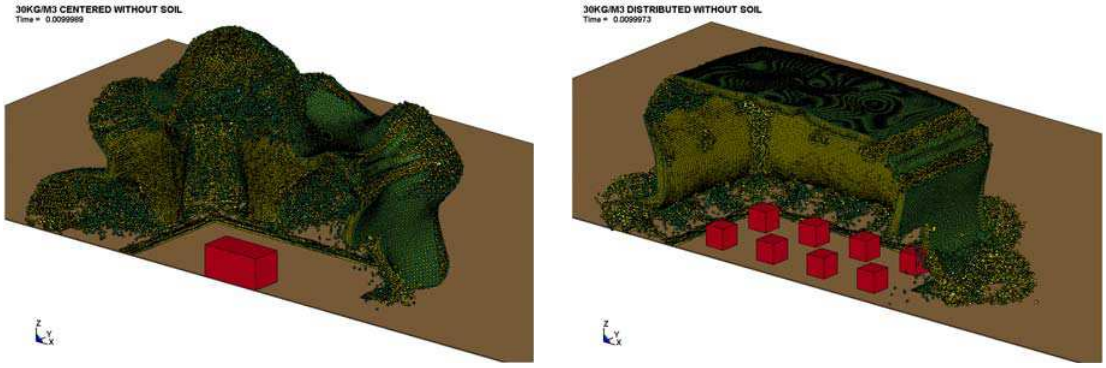


(a) (b) (c)

Figure 1 RC slab response (a) after the shock impulse and (b) after the gas pressure phase under a loading density of 0.25kg/m^3 and (c) after shock impulse under a loading density of 2kg/m^3

3.2 Influence of Charge Distribution and Charge Shape

With calibration of the ALE model to simulate the detonation of TNT being performed, a series of aboveground magazines (AGM) and earth-cover magazine (ECM) are simulated [2]. A rectilinear shape was chosen as opposed to a spherical charge as the overpressure and impulse histories are closer to values from the TM5-1300. The structural modelling details will be discussed in the following section. Under high loading density, it is observed that the overpressure and impulse in certain locations within the confinement of the ECM are higher than the complementary AGM cases and this was attributed to the soil cover which to some extent constrains the structural deformation and strengthens the overpressure reflection effect in those locations. It is observed also that although the load density may be similar, the distribution and arrangement of the charges may influence the structural response as seen in Figure 2. Similar structures were under low loading density and it was observed that the loadings within ECM and AGM do not differ significantly. However, the simulation again shows the significance of the distribution of the charge in the model.



(a) (b)

Figure 2 Difference in structural response under different arrangement of TNT

From these studies, it is evident that the structural composition and the load interact to determine the response of the RC structure. Therefore, the following section will summarise critical parameters that must be well taken into consideration of the modelling as well as assumptions made in the construction of the numerical structural model.

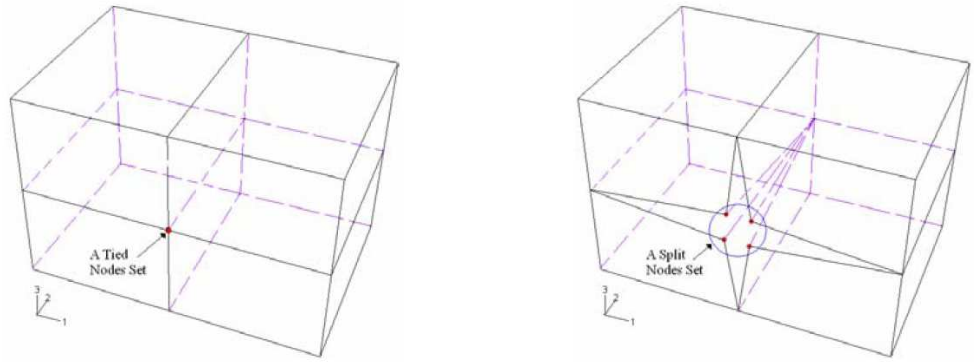
4. Structural Response and Breakup

4.1 Element Erosion

The structural response and breakup phase is the link between the loading phase and the debris launch phase. In the initial part of the project, a considerable amount of effort is spent to review the existing literature on concrete and steel material. The focus of the material failure under explosion loading is focused more on concrete as it has a much lower tensile strength and its constitutive properties are much more sophisticated than steel. The more advanced concrete models like the Concrete Damage Model in LSDYNA and RHT Concrete Model in AUTODYN was studied and compared [3]. It was concluded that the Concrete Damage model coupled with the element erosion criteria to simulate concrete fracture depicts the concrete breakup better. The erosion criterion is based on maximum principal strain (positive for tension) of concrete element and steel reinforcement is assumed to have a perfect bonding with the concrete element. While the model produce realistic breakup model for loading density less than $1kg/m^3$, the model will suffer from massive element erosion for loading density more than $2.5kg/m^3$.

4.2 Nodal Splitting Method

A nodal-split methodology was introduced to eliminate excessive loss of concrete elements due to erosion (see Figure 3) with the elements breaking apart at their nodes as opposed to eliminating them. The CONSTRAINED_TIED_NODES_FAILURE card in LSDYNA is used for this work and the influence of the plastic strain at failure is studied [4,5,6].

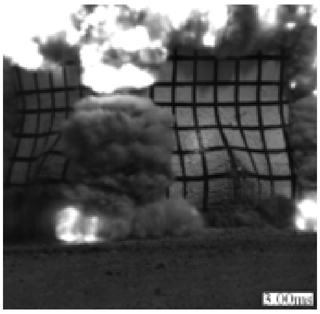


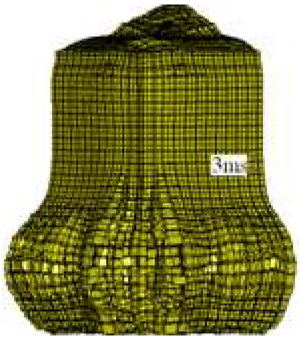
(a) (b)

Figure 3 Constrained nodal tie (a) before and (b) after failure

With reference to the preceding two paragraphs, it is evident that the influence of the maximum element tension strain $\varepsilon_{\max}$ and maximum nodal plastic strain may be critical parameters to consider. The maximum element tensile strain criterion has a strong influence on the gas pressure history, launch velocity and breakup pattern. The use of low $\varepsilon_{\max}$ values will result in the increase of venting gaps and thus a drop in gas pressure duration. With an increase in $\varepsilon_{\max}$, the displacement and velocity decreases slightly due to the increase consumption of energy in failing the element. By setting $\varepsilon^{p}_{\max}$ to 0.1, an appropriate value for $\varepsilon_{\max}$ could range between 0.5 and 2.0 as calibrated with experimental testing of a RC structure (Kasun) with a loading density of 20kg/m^3 as illustrated in Figure 4 [4, 11].

Experimental | Simulation | Experimental | Simulation





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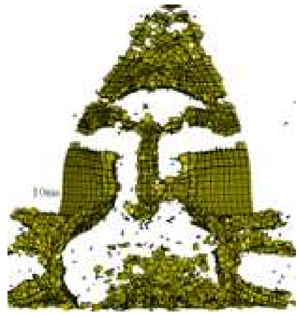


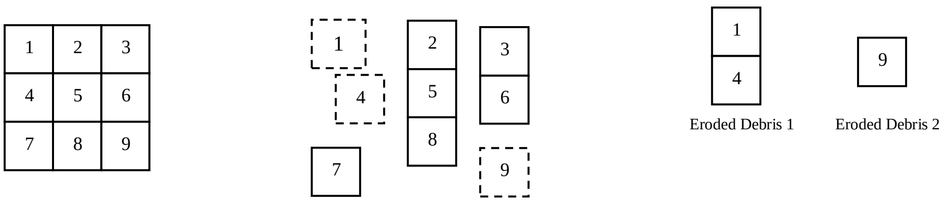
a. t = 3ms b. t = 10 ms

Figure 4 Experimental and numerical simulation results for a RC structure (Kasun II test) at 3ms and 10ms

4.3 Formation of Debris

The breakup of the structure is simulated by either the element erosion method or the nodal splitting method or a combination of both methods. The debris are formed out of the pool of eroded elements and un-eroded elements. Data on the element identification and erosion time of the eroded elements can be retrieved from the analysis and the time duration of the initial response is divided with a time interval Δt^{GE}. Eroded elements within each time interval will then be extracted and grouped. In each group, the algorithm will check the initial connectivity of the elements to assess whether these elements can be assumed to form a piece of debris as illustrated in Figure 5.

For the non-eroded elements, an algorithm will gather the current distance of all nodal pairs in close proximity from the results of last time step. If the distance is greater than a specified maximum distance $d_{\max}^{cpp}$, the pair of nodes is considered to be separated. Theoretically, a nodal pair will split as long as $d_{\max}^{cpp}$ is not equal to zero. However, numerous hairline cracks exist within a single piece of debris and therefore a non-zero value is assigned to $d_{\max}^{cpp}$. The element distance $d_{\max}^{cpp}$ is further refined into two separate values for different elements. One is for the mix-mix element nodal pair namely d_{m}. Another is for the mixed-concrete and concrete-concrete element nodal pair, namely d_{c}. Through calibration with Kasun test, it was found that a value of 2.0mm and 0.425mm for d_{m} and d_{c} respectively corresponds better with the test results [5].



(a) Initial connectivity between elements

(b) Nodal split and eroded elements (dashed) at an arbitrary Δt^{GE}

(c) Extraction of the constitution of debris mass from the eroded elements

Figure 5 Illustration of data extraction algorithm to eroded elements

5. Debris Launch and Trajectory

After the debris size and numbers are determined via the algorithm described in section 4, the debris launch velocity and launch angles are determined by averaging the elements respective velocities and angles. For the debris launch angle, its values are very much tied to the response (or loading density) and the time of breakup of the elements. The methodology of the debris trajectory and calculation of the debris IBD line has been cover in the other paper by Fan in this seminar [8] and will not be repeated in this paper. Instead, the following paragraphs will concentrate on discussing the pros and cons of the work done so far and suggestion for further improvement.

5.1 Debris Mass Distribution

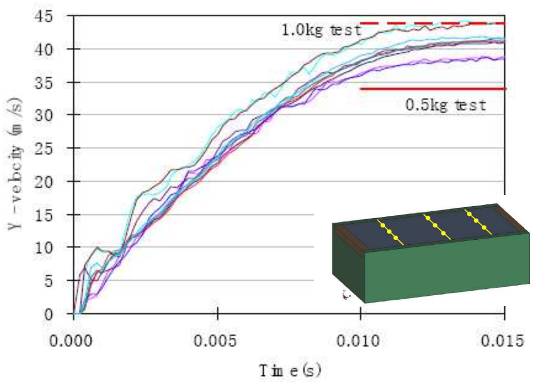
In the prediction of debris hazard, the number of debris and its mass, coupled with its velocity are important parameters that will determine the energy and lethality of the debris. Under the U.S Technical Paper 21, the debris mass can be categorised into 10 different mass bins : Mass Bin 1 having largest debris mass of more than 24.5kg to the smallest Mass Bin 9 and Mass Bin 10 which has a mass between 0.023kg to 0.054kg and 0.011kg to 0.023kg respectively [9]. For the numerical simulation work, the smallest concrete element is about 33mm x 33mm x 25mm which will roughly have a mass of about 0.065 kg. Thus, the smallest concrete element will only correspond to the Mass Bin 8 which has a mass between 0.054kg to 0.136kg. Therefore, the physical element size will have a bearing on the accuracy of the debris mass distribution especially in the class of Mass Bin 8 to Mass Bin 10. To overcome this problem, a finer mesh and subsequently more computational powers will be required.

5.2 Debris Launch Velocity

The debris launch velocities are generally well predicted by the numerical simulation. Figure 6 shows a good agreement between concrete slab velocity from the simulation versus the recorded velocity [3]. The clamped concrete slab test recorded an average velocity of 34m/s and 44m/s for loading densities of 0.5 kg/m^3 and 1kg/m^3 respectively compares well with simulated velocities range from 38m/s to 44 m/s.

It should also be noted that the breakup and erosion criteria will affect the internal loading and hence the velocity of the debris slightly [4]. To check the suitability of the breakup criteria, the initial breakup pattern and velocity from the numerical simulation can be checked with the high speed videos of experimental specimens.

(a) Clamped slab test



(b) Numerical simulation results for clamped slab test

Figure 6 Clamped slab test and numerical simulation with measurement of slab launch velocity

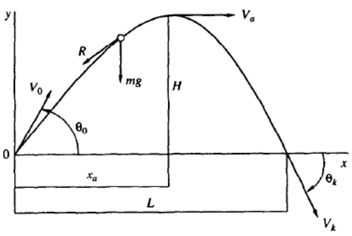
5.3 Debris Launch Angles.

The debris launch angles prior to their trajectories can be obtained from the numerical simulation results directly after their velocities have stabilised. Each debris has its unique launch angle and launch position. It is also noted that high loading densities produced debris with a small distribution of launch angles as compared with lower loading densities which is somewhat consistent with its deformation response and breakup. In summary, numerical simulation of the launch angles are relatively straight forward and their accuracies are dependable on the accuracies of their response and breakup.

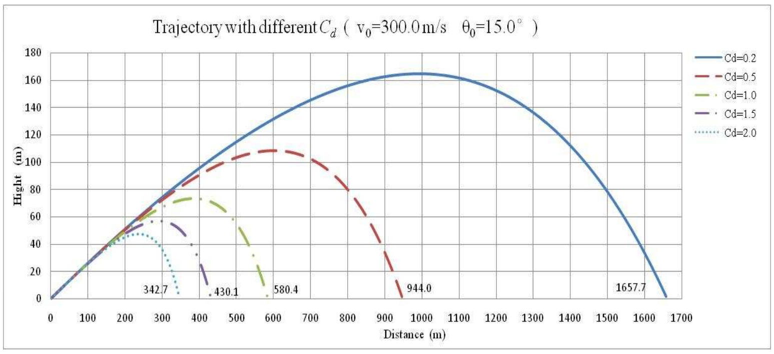
6. Debris Trajectory and Post Ground Impact

6.1 Debris Flight Path

The simulation of the debris flight path is from an in-house developed code called DeThrow whereby debris is consider as a singular object under gravity and air drag forces. Parametric studies for a range of assumed air drag coefficient C_d were conducted and it was found that C_d = 1.2 agrees rather well with Kasun test data [2]. In this study, it was also found that the final debris range is very sensitive to value of C_d as shown in Figure 7.



(a) Debris trajectory path



(b) Debris trajectory path with various assumed drag coefficient

Figure 7 Debris trajectory sensitivity study for drag coefficient

DeThrow assumes that individual debris flight can be independently calculated by considering that the drag coefficient is a constant value for all debris. However, an independent study by TNO suggested that the debris pieces are projected out initially as a close packed debris slab or mass rather than individual debris piece [12]. The slab and wall is launched as a single debris or thick “debris cloud” whereby debris as so closely packed to each other that there drag coefficient cannot be simplified as a singular debris.

6.2 Post Impact Roll and Ricochet

When the debris first impact the ground, the debris is expected to roll, ricochet and further breakup. These phenomena are important. Most of the test data are collected based on the debris final resting range and comparison with numerical simulation results should therefore account for such phenomena. This project did not conduct any experiment to quantify the post impact roll and ricochet but assume that the following relationships [10]:

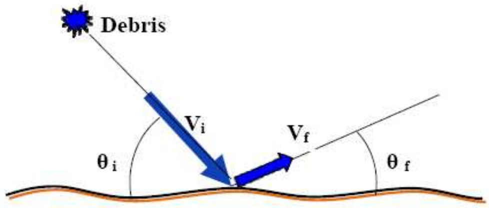


Figure 8 Roll and ricochet for debris

$V_f = 0$; $\theta_f = 0$ for $\theta_i \geq 13°$ and $V_i \geq 18$ m/s

$V_f = (1.0\text{-}0.00476\theta_i)\ V_i$; $\theta_f = 0.484\theta_i$ otherwise

It was further assumed that there is no further breakup upon impact with the ground and the post impact velocity V_f and ricochet angle θ_f will be the input parameters for the debris second launch trajectory. The preliminary study has shown that assuming that the debris are allowed to ricochet twice provided that the velocity by and incident angle condition are satisfied provided a better fit to the test data [6].

6.3 Future Works for Debris Trajectory and Post Ground Impact

The simulation of the debris trajectory and post ground impact is largely based on existing literature. It is apparent that due to the sensitivity of the drag coefficient on the final debris range, there is a need to characterize the drag coefficient or its related parameters better. This includes a need to define the drag coefficient for the various shapes, sizes of the debris pieces and the influence of velocity on the drag coefficient. Another area of study could also include the "cloud effect" on the drag coefficient and the effect of debris spinning on the final debris range. The wind tunnel test coupled with numerical simulation could potentially shed some light into this topic.

Future work will also include the study of debris roll and ricochet coupled with debris breakup upon hitting the ground. Experimental work can be conducted to determine the additional range resulted from debris ricochet and also quantify the amount of debris breakup. The internal debris damage or fracture prior to impacting the ground is an important parameter that can affect the breakup will also be studied.

7. Conclusion

Numerical simulation of the debris hazard for a reinforced concrete structure is a complicated problem and the phenomenon has been broadly categorized into 5 main phases. Each stage of the phenomenon has its unique challenges and different subtopics for each stage are identified, review and studied upon. In general, the internal blast modelling phase is relatively easy compare to the modelling of the structural response and breakup. The structural response will in turn affect the debris launch. The final two phases on debris trajectory and post ground impact needs further studies numerically and experimentally to provide more insight to correlate explosion test data with numerical simulation results. Table 1 summarizes the parameters influencing the debris simulation and its state of art. A more comprehensive description of the table and justification for ease of simulation and state of art for the various parameters is given in ***Appendix 1***.

Table 1 Summary of the Parameters Influencing the Debris Simulation

Simulation Phase	**Parameter**	**Ease of Simulation**	**State of Art**
Loading	Shock pressure	Easy	Satisfactory
	Impulse history	Easy	Satisfactory
	Gas pressure / venting effect	Moderate	Satisfactory
	Modeling charge distribution	Moderate	Well established
	Charge shape	Easy	Well established
Structural Response & Breakup	Modeling of steel rebar	Moderate	Satisfactory
	Breakup criteria for erosion	Moderate	Limited
	Breakup criteria for nodal split	Moderate	Limited
	Debris formation criteria	Difficult	Limited
Debris Launch	Debris Size and numbers	Difficult	Limited
	Debris launch velocity	Moderate	Satisfactory
	Debris launch angles	Easy	Satisfactory
Debris Trajectory	Drag coefficient	Moderate	Limited
	Debris cloud effect	Difficult	Limited
	Debris spinning	Difficult	Limited
Post Ground Impact	Roll and ricochet	Moderate	Limited
	Internal damage within debris	Difficult	Limited
	Further breakup	Moderate	Limited

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Appendix 1

Table 1 Summary of the Parameters Influencing the Debris Simulation

Simulation Phase	Parameter	Comments on Importance of the Parameter to the Numerical Simulation	Ease of simulation	State of Art
Loading	Shock pressure history	Under conditions of low loading density or situations where overall structural response dominates, shock is less influential. Contrary, shock pressure history will be significant when local or material response dominates.	Easy	Dependant on structural response and experimental data is incompatible with results from design parameters. Validation of this effect is not directly available and is required to validate blast pressure. State of art is satisfactory.
	Impulse pressure history	Under conditions of low loading density or situations where overall structural response dominates, shock is less influential. Contrary, shock pressure history will be significant when local response dominates.	Easy	
	Gas pressure / Venting effect	Under low loading density, structural response may cause an increase in the loading duration of the gas pressure phase. This will increase the impulse that is exerted on the structure as observed in an experiment.	Moderate, as the effect is dependant on the structural response, which by itself must be fairly accurate in order to validate the venting effect	
	Modeling charge distribution	In the modeling of the charges, it is important to model the distribution of the charges as close as possible to reality as the structural response will be different.	Moderate, as the accuracy of combined effect of various detonation has to be validated	Effect of combined detonation has to be validated but an experiment to validate it is not difficult.
	Charge shape	Rectangular charges results are closer to that of the TM5 recommendations. Difference more significant at larger scaled distances. Thus, for ammunition storage the influence of charge shape may be less influential.	Easy	The accuracy is dependent on the numerical calculation as experimental information is available based on the expertise on shaped charges.

Structural Response	Modeling of reinforcement steel bar elements	Reinforcement bar details are observed to more significant under low loading density when overall structural response dominates. Explicit modeling of the reinforcement bars can be modeled using mix elements, which saves resources and is compatible with the nodal split methodology. However, the assumption of full composite effects and non-physics assumption of erosion criteria for crack propagation.	Moderate, as the accuracy of modeling reinforcement bar is dependant on the computational resources available	The current knowledge of reinforcement bar is sufficient to model the reinforcement bars but large scale modeling is dependent on the computational resources.
	Breakup criteria for erosion	Both maximum tension strain criteria for steel and concrete have a strong influence on the gas pressure history, launch velocity and breakup pattern.	Moderate, as it easy to input but material validation is required	The current state of art for erosion is still not sufficiently matured to be fully implemented in numerical model due to the loss of mass which will violate the law of conservation of mass which is an important concept in numerical simulation.
	Breakup criteria for nodal split	Maximum nodal plastic strain has a significant effect on the launch parameters of the debris and less influence on the breakup pattern and pressure history and a different criterion for plain concrete and mix elements will improve fidelity.	Moderate, as it is easy to input but material validation is required	This concept is novel and may be a more viable option as opposed to element erosion but experimental validation of the material is required to ensure the failure criteria is not just empirically sound but also based on physics.
	Time interval Δt^{GE} (for eroded elements)	Time interval Δt^{GE} for the prediction of debris from eroded elements is more significant under low loading density where the proportion is eroded element is larger.	Difficult, as the technique is a modeling technique based and a more physics-based approach is required	This technique is the most suitable approach identified by the research team so work is required to find a more physics-based approach to tackle the eroded element and nodal distance criteria.
	Debris formation criteria : Maximum nodal distance (for non-eroded elements)	By having two different criteria for concrete and mix elements, will influence the debris number distribution but the contribution of the criteria of concrete is more significant than that of the mix elements.	Hard, as the technique is based on empirical data and a more physics-based approach is required	
Debris Launch	Debris size and numbers	The size and numbers of debris will be affected by the erosion and nodal split criteria. In addition, the smallest debris size can only be model will sufficient fine mesh size smaller than 10mm.	Difficult.	The criteria for determining if the element separation is merely a crack or two distinct debris need further verification. Finer mesh size is also limited by computational resources.
	Debris launch velocity	The debris launch velocity one of the key parameters as the energy is proportional to square of its velocity.	Moderate	The average velocity can be reasonably well predicted especially for lower loading densities.

	Debris launch angles	The launch angles are influenced by the response of the structure. Important parameter for the subsequent trajectory of the debris.	Easy	Debris launch angle can be easily verified by high speed videos of the initial breakup of the structure.
Debris Trajectory	Drag coefficient	The drag coefficient will greatly influence the debris throw range and its values dependant on its shape, surface roughness and velocity.	Moderate	Debris drag coefficient for various debris shape, size and velocity can be established via numerical simulation or wind tunnel test.
	Debris cloud effect	Will affect the drag coefficient which in turn affects the debris throw range.	Difficult	Debris cloud effect could possibly be investigated via numerical simulation. Limited test data so far.
	Debris spinning	Will affect the drag coefficient and assumption of a laminar air flow around a debris piece. The debris range can greatly be increased when a debris is spinning as opposed to it not spinning.	Difficult	Based on current testing methods, difficult to establish the spinning phenomenon of debris. Limited test results so far.
Post Ground Impact	Roll and ricochet	The roll and ricochet phenomenon is important because numerical simulation results are calibrated and compared with the debris pickup test data. If such data are “skewed” by the roll and ricochet, this needs to be accounted for in numerical simulation.	Moderate	Roll and ricochet of masonry debris has been studied. Similar study can be repeated for concrete debris by varying the type of surfaces, the angle of incidence and velocity etc.
	Internal damage / fracture within the debris	This could be an important parameter that will have a strong influence if the debris will breakup upon ground impact	Difficult	Hardly any study has been conducted so far to quantify the damage of existing debris in flight prior to impact on ground.
	Further breakup upon impact on ground	This parameter is important because it may cause a skew in the number and mass of debris collected	Moderate	Limited study has been conducted. It is possible to design test to investigate the breakup of debris based on the level of damage in the concrete debris.

34th DoD Explosive Safety Seminar
Portland, Oregon

A Review : Numerical Modeling of Debris Throw of RC Structures Under Internal Explosions

Lim Heng Soon
DSTA

Defence Science & Technology Agency

Co-Workers

Defence Science & Technology Agency (DSTA)

Lim Heng Soon

Kang Kok Wei

Nanyang Technological University (NTU)

Prof Fan Sau Cheong

Dr Yang Yaowen

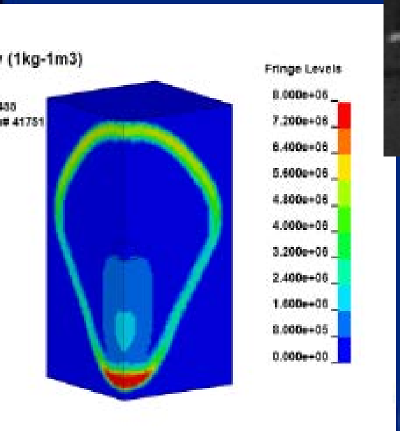
Dr Yu Qingjun

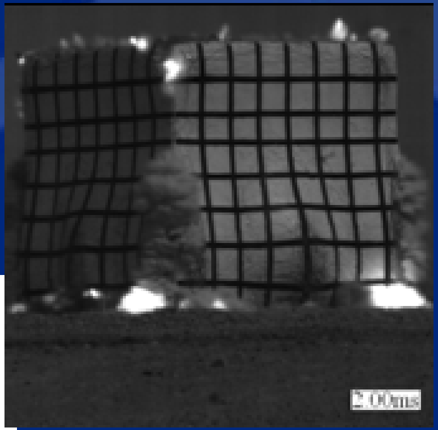
Background

- DSTA & NTU collaboration project.
- To develop a methodology to simulate & predict debris throw for high explosives storehouses.
- Motivation : for a more accurate prediction of the debris Inhabited Building Distance (IBD) hazard.
- Project concentrate on box shaped reinforced concrete structures.
- Various stages of this project has been reported in past DDESB seminars.

5 Phases

Internal Blast Loading → Response & Breakup of Structure → Debris Launch → Debris Trajectory → Post Ground Impact





FOI & NDEA : Kasun test structure

Internal Loading

- Loading is influenced by the response and breakup due to venting.

  ==> CFD and CSD coupled simulation

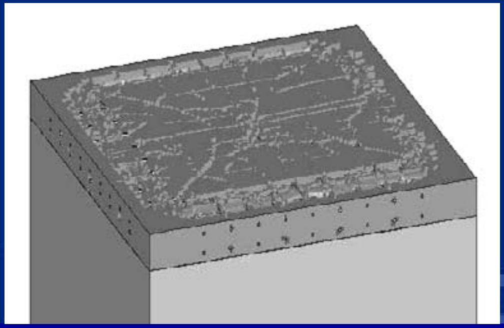
- Various key parameters are examined.

i. Shock & Gas Loading

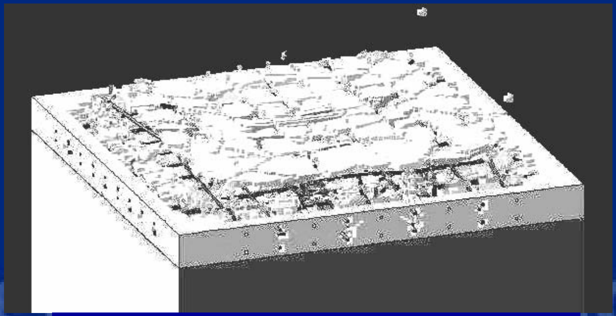
- Low loading density vs high loading density

- Failure & breakup of the structure simulated via "Element Erosion" technique in LS_DYNA

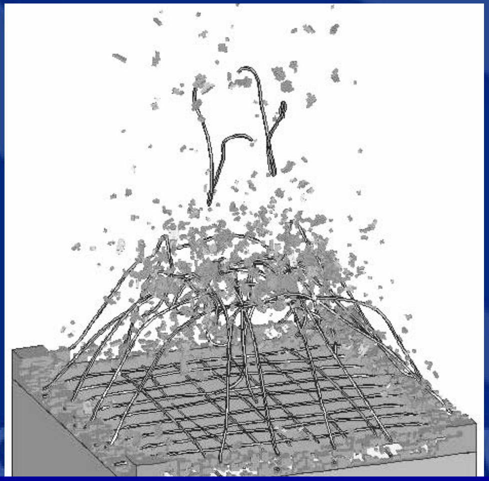
- Influence of various loading densities



Loading density = 0.2kg/m^3



Loading density = 0.3kg/m^3

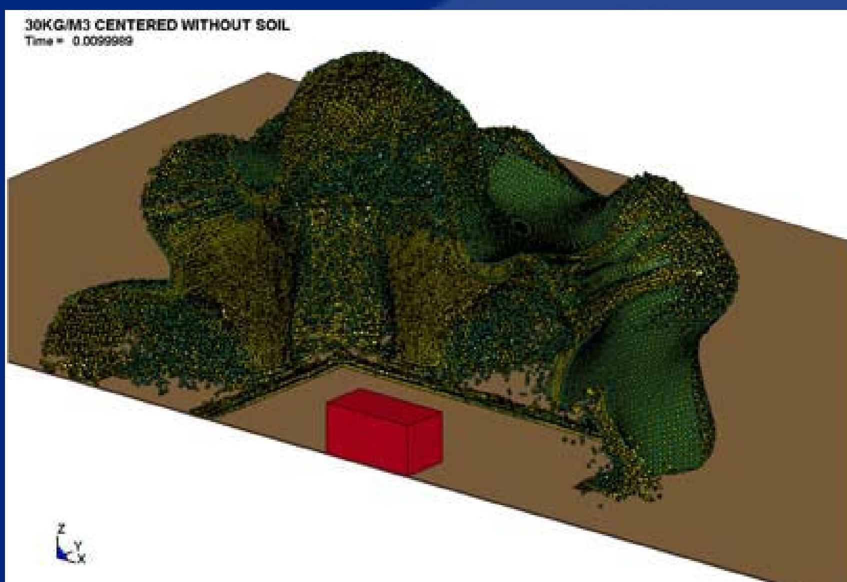


Loading density = 2.0kg/m^3

Internal Loading

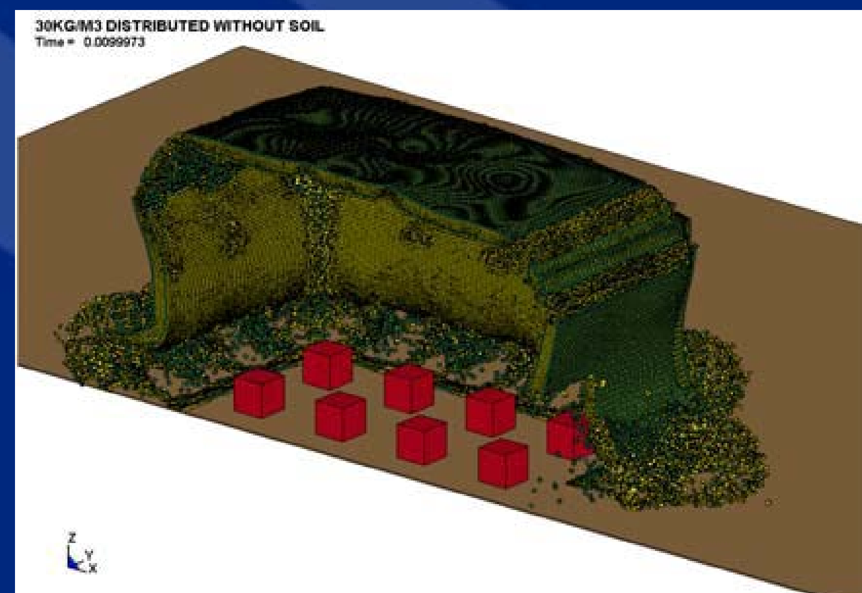
ii. Influence of Charge Distribution

- Strong influence on response of structure



Single Concentrated Charge

(Charge weight = 15,000kg
Loading density = 30kg/m^3)



Distributed Charge

(Charge weight = 15,000kg
Loading density = 30kg/m^3)

Response & Breakup

i. <u>Element Erosion</u>

- Technique used in Finite Element Modeling to simulate breakup of the structure

- Leads subsequently to the formation of concrete debris.

- Problems with erosion techniques :

    a. Phenomenon not real

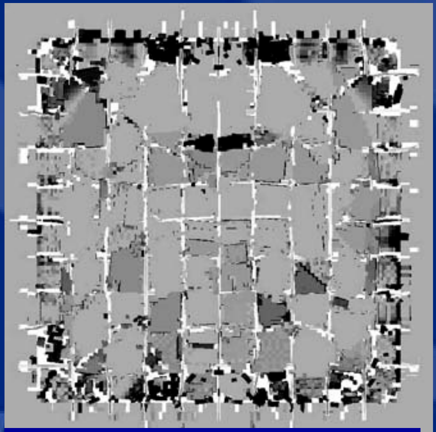
    b. Loss of element

- Criteria for erosion based on maximum principal strain.

- Applying concrete strain failure criteria leads to massive erosion of elements.

- Gets rather realistic breakup prediction for lower loading density (say up to 1 to 2 kg/m^3)

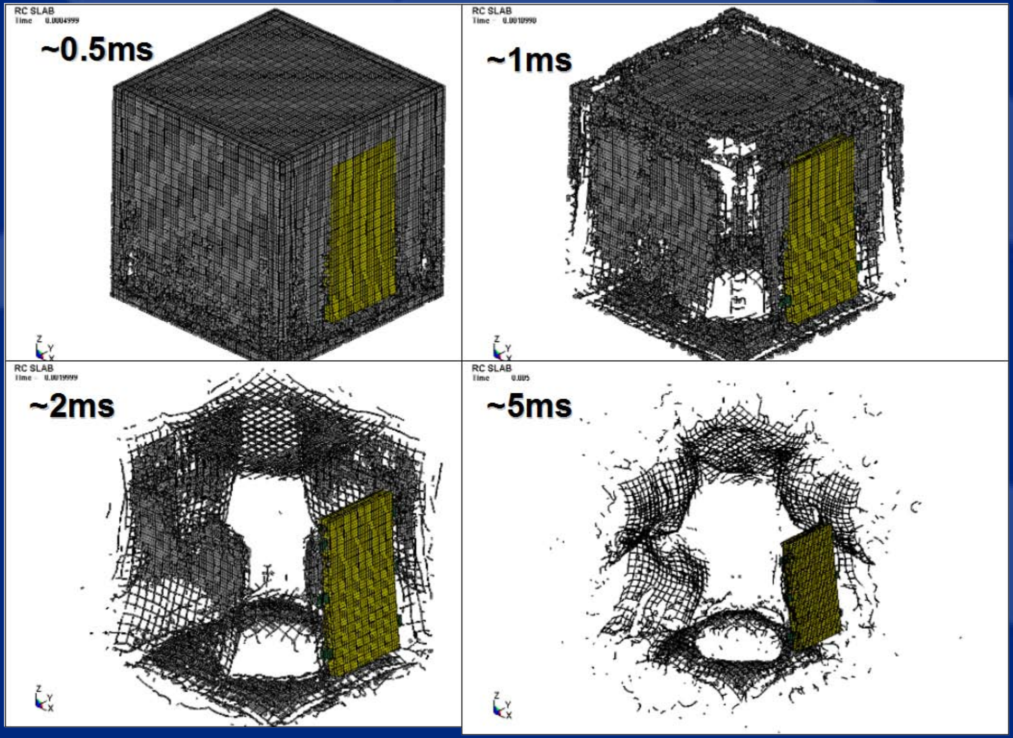
Test results : EMI Clamped DLV, Loading density = 0.3kg/m^3)



Simulated results

Response & Breakup

- Massive loss of elements using erosion technique
- Example : Simulation of Kasun test structure



Kasun Test (LD = 10kg/m^3)

FOI & NDEA : Kasun test structure

Response & Breakup

ii. Nodal Splitting Method

- Technique introduce to eliminate excessive loss of elements

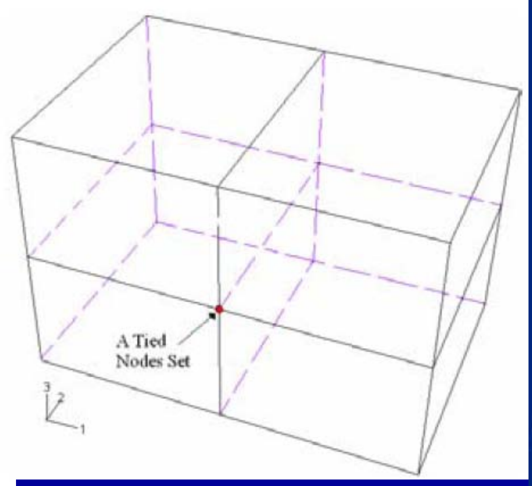
- CONTRAINED_TIED_NODES_FAILURE in LS_DYNA

- Nodal strain assumes the average value of surrounding elements.

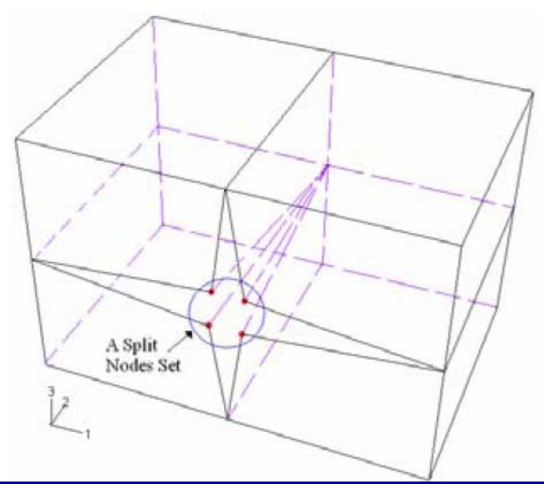
- Element is split when nodal strain exceeds a failure criteria.

- Current value based on empirical data fitting.

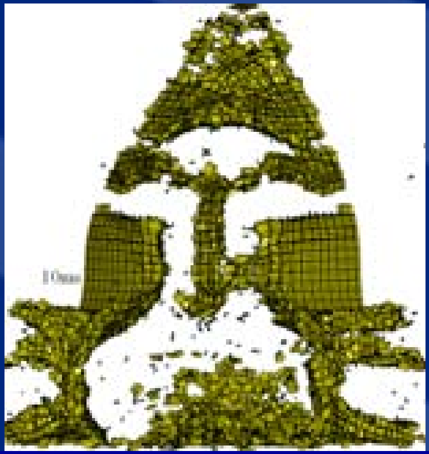
- Numerical simulation is coupled “erosion” with “nodal splitting” method.



4 elements tied together



4 elements split when node fail



Simulation of Kasun (loading density = 20 kg/m^3) assuming quarter symmetry.

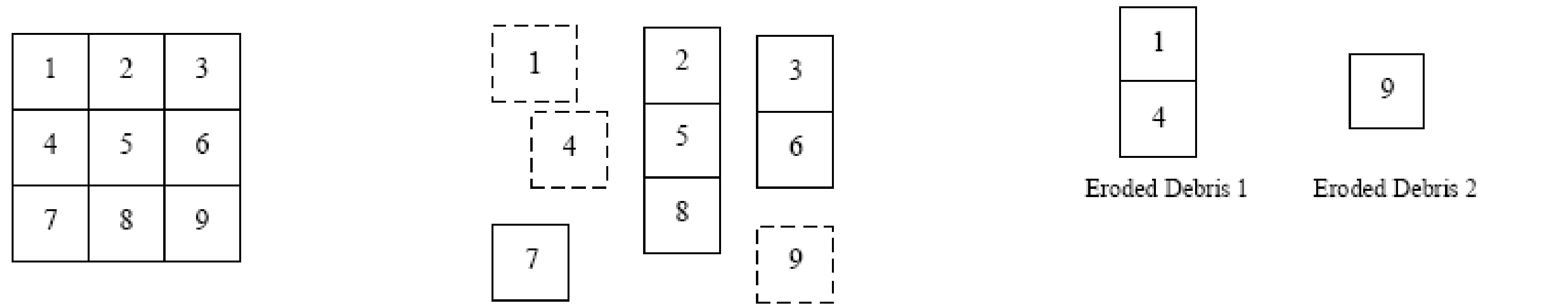
Response & Breakup

iii. Formation of Debris

- Criteria for determination of debris before being projected into the air.

- Eroded elements : Based on erosion time interval,

- Un-eroded elements : Based on specified maximum distance between nodal pairs



(a) Initial connectivity between elements

(b) Nodal split and eroded elements (dashed) at an arbitrary Δt^{GE}

(c) Extraction of the constitution of debris mass from the eroded elements

Debris Launch

• Refers to the short duration between structure breakup and debris flight in air.

• Various key parameters include debris mass distribution, launch velocity and angle.

• Values very much influence response and breakup of the structure.

i. <u>Debris Mass Distribution</u>

- Simulated debris mass are grouped into Mass Bins (1-10) defined in DDESB Technical Paper 21.

• Mass Bin 9 (23g - 54g) and Mass Bin 10 (11g - 23g) are the smallest debris.

• Computationally very expensive to capture all mass bin data.

• Kasun simulation : smallest element : 33 x 33 x 25mm which correspond to 65g which falls into Mass Bin 8.

Debris Launch

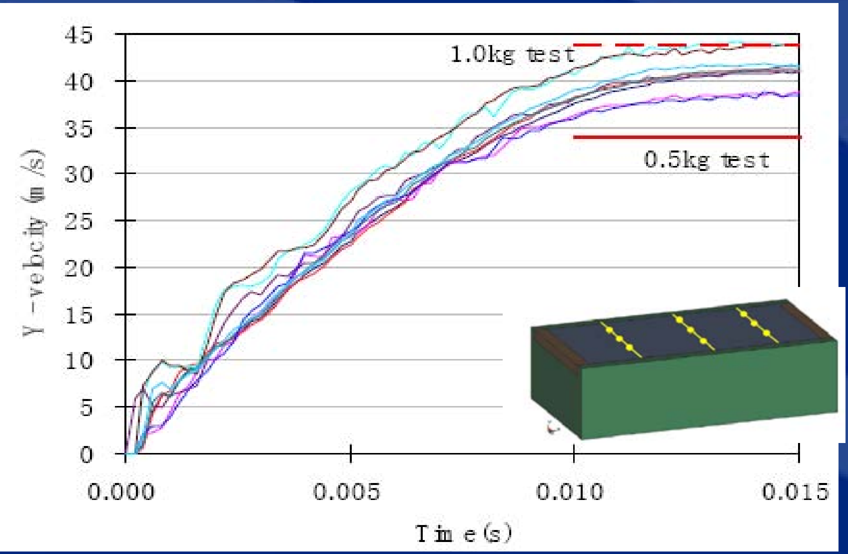
ii. Debris Launch velocity

- Generally well predicted by the numerical simulation.

- Accuracy could be affected partially by the breakup which in turns affect the venting and internal loading.

- Launch velocity is generally more sensitive to the erosion criteria rather than the nodal splitting criteria.

Clamped slab test (TNO)



Numerical simulation results for clamped slab test

Debris Trajectory

• Refers to the debris flight in air just before impact unto the ground.

• More detail description of the methodology given "Study of Debris Throw" presentation.

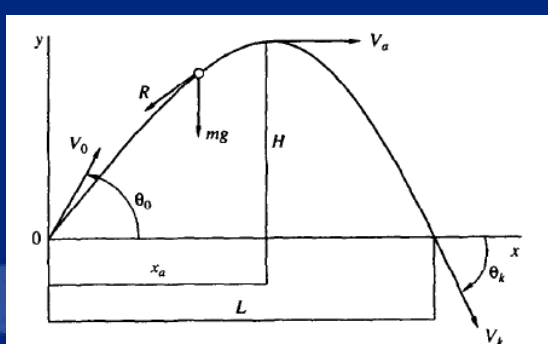
i. <u>Debris Flight Path</u>

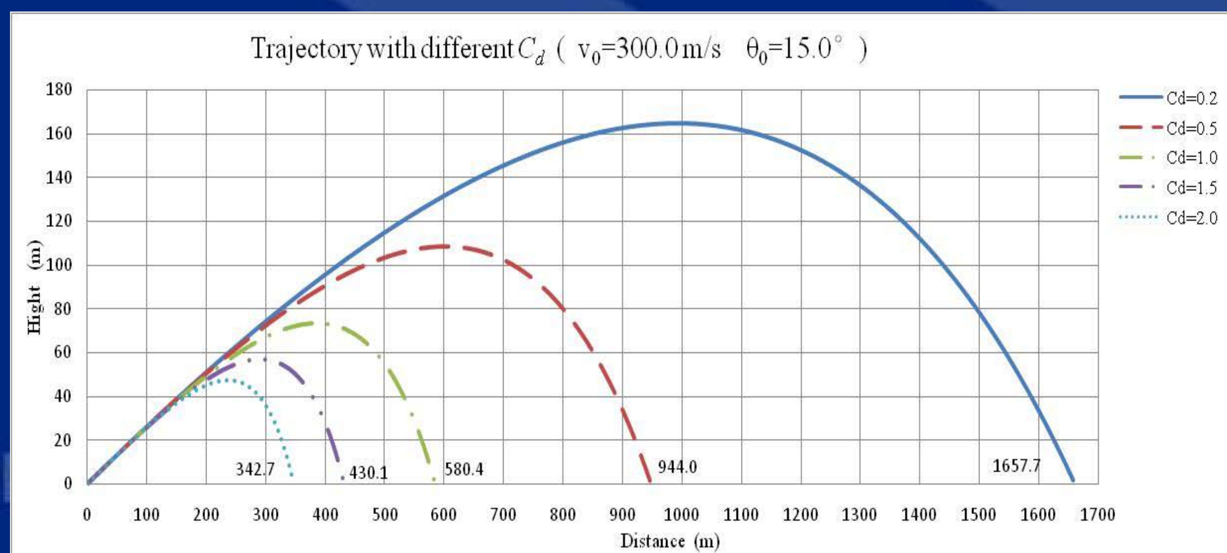
• Debris trajectory calculation is based on an NTU in-house code DeThrow.

• Takes into account air drag and gravity of singular debris.

• Assumes a singular drag coefficient for all debris.

• Final debris range is very sensitive to the air drag coefficient.





Debris Trajectory

Other related parameters :

• Validity that debris fly as an independent debris especially in the early stage of the trajectory is questionable.

→ TNO study on debris cloud

• Debris spinning creating the “Magnus Effect”

→ Spinning create a lifting effect on the debris thereby increasing the range.

• Some of these phenomenon can be investigated via numerical simulation and laboratory testing.

→ To be investigated in the next phase of the project

Post Ground Impact

• Refers to the phase whereby debris impact unto the ground and its subsequent movement.

• It is of concern because our simulation results are calibrated from collected debris test data which are subjected to these phenomenon.

• Includes :

i. Post impact roll & ricochet

ii. Further breakup upon ground impact

→ Dependant on the internal damage or fracture of debris

Parameters Influencing the Simulation of Debris Hazard

Simulation Phase	Parameter	Ease of Simulation	State of Art
Loading	Shock pressure	Easy	Satisfactory
	Impulse history	Easy	Satisfactory
	Gas pressure / venting effect	Moderate	Satisfactory
	Modeling charge distribution	Moderate	Well established
	Charge shape	Easy	Well established
Structural Response	Modeling of concrete & steel rebar	Moderate	Satisfactory
	Breakup criteria for erosion	Moderate	Limited
	Breakup criteria for nodal split	Moderate	Limited
	Debris formation criteria	Difficult	Limited
Debris Launch	Debris Size and numbers	Difficult	Limited
	Debris launch velocity	Moderate	Satisfactory
	Debris launch angles	Easy	Satisfactory
Debris Trajectory	Drag coefficient	Moderate	Limited
	Debris cloud effect	Difficult	Limited
	Debris spinning	Difficult	Limited
Post Ground Impact	Roll and ricochet	Moderate	Limited
	Internal damage within debris	Difficult	Limited
	Further breakup	Moderate	Limited

Conclusion

- Numerical simulation of the debris hazard is a very complicated problem
- Entire process simplified into 5 main phases.
- Each phase consist key parameters that could be sub-studies by themselves.
- Unique challenges in each phase and key parameters.
- Final two phases on debris trajectory and post ground impact needs further study.
- Demonstrated the feasibility of using numerical simulation, coupled with sufficient test data, in studying such sophisticated problems.

Thank You